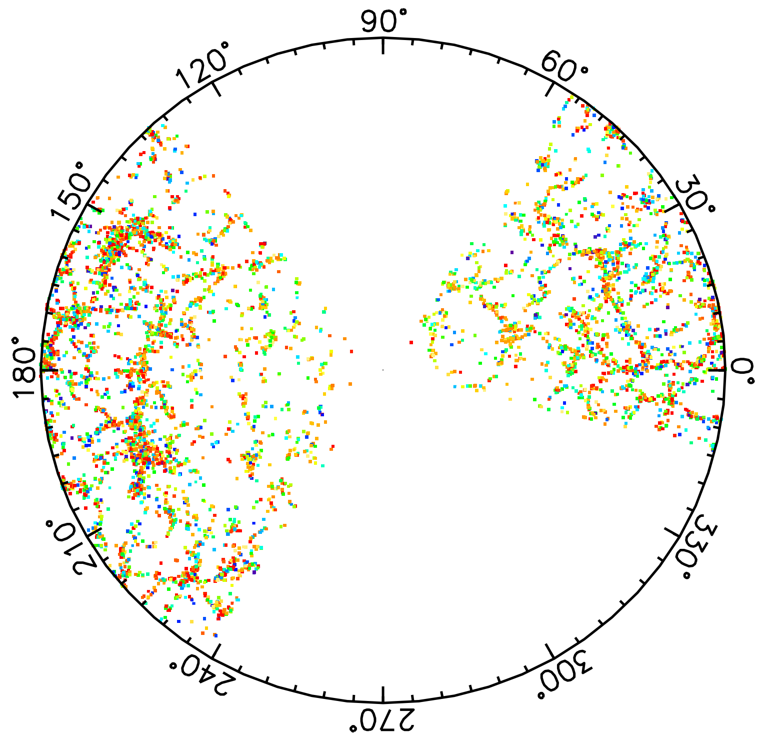
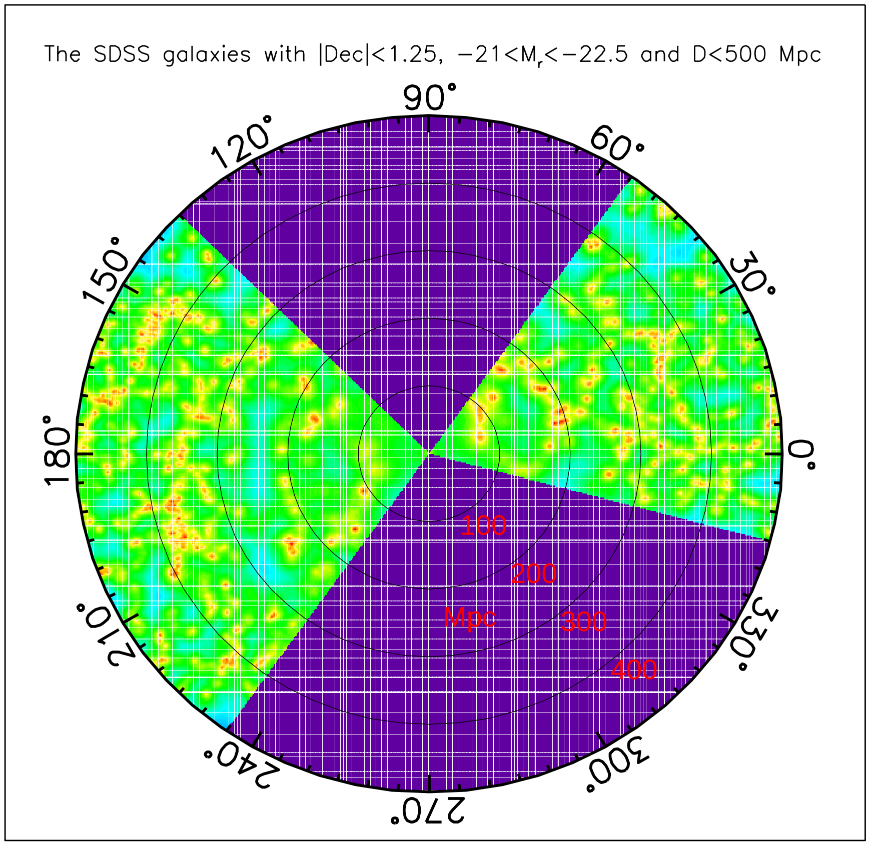
Astr 323: Extragalactic Astronomy and Cosmology

Spring Quarter 2014, University of Washington, Željko Ivezić

Lecture 6:

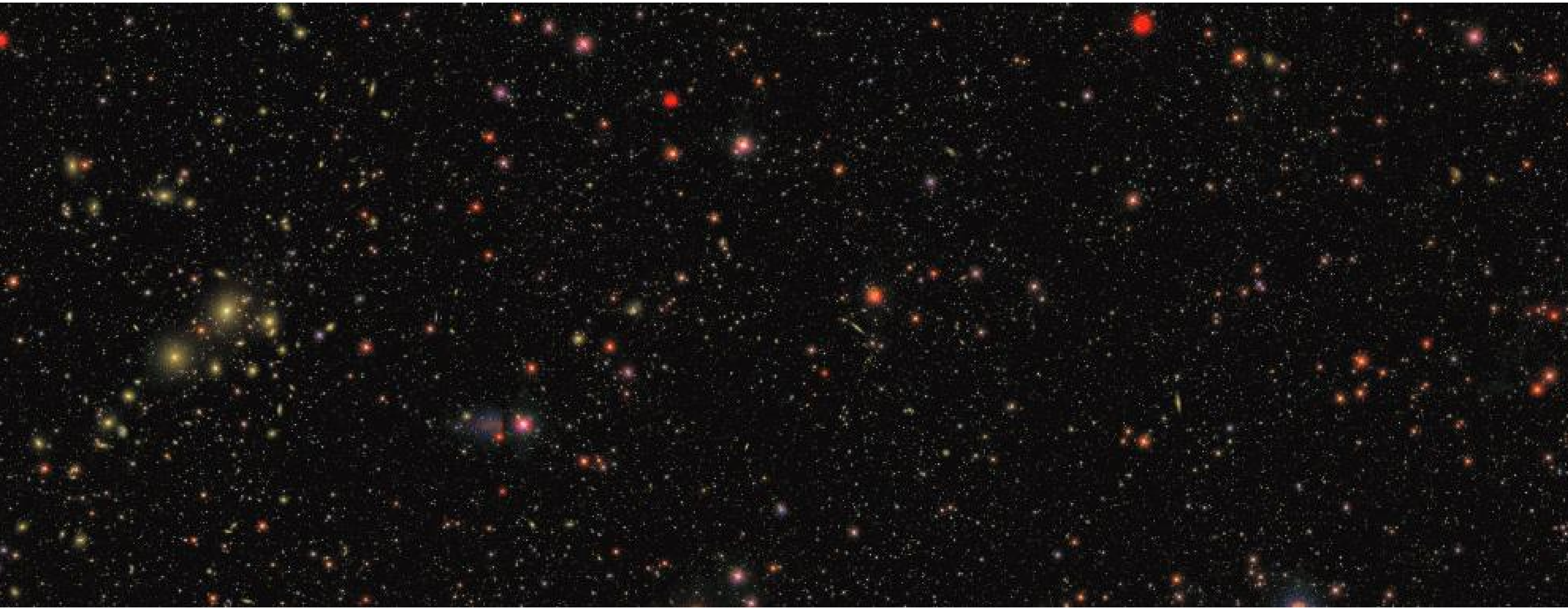
Galaxy Clusters, Gamma-ray bursts, Lensing





Large-scale distribution of SDSS galaxies

- Top left: each dot is a galaxy with $-22.5 < M_r < -21$ (and $|Dec| < 1.25^{\circ}$), color-coded by $u - r$ color
- Bottom left: implied number density distribution
- Galaxy distribution is not homogeneous: excess of high density peaks
- Red galaxies more strongly clustered than blue galaxies
- Clustering strength also increase with luminosity



Perseus cluster of galaxies (SDSS gri color composite, $\sim 2/3^\circ \times 1/4^\circ$)

Why are galaxy clusters interesting?

0) They are the largest virialized structures in the Universe

1) Formation and evolution of galaxies

2) Large scale structure of galaxy distribution (e.g. superclusters)

3) Gravitation lensing (dark matter)

4) Cosmological parameters (from cluster mass function)

Modern Methods for Finding Clusters

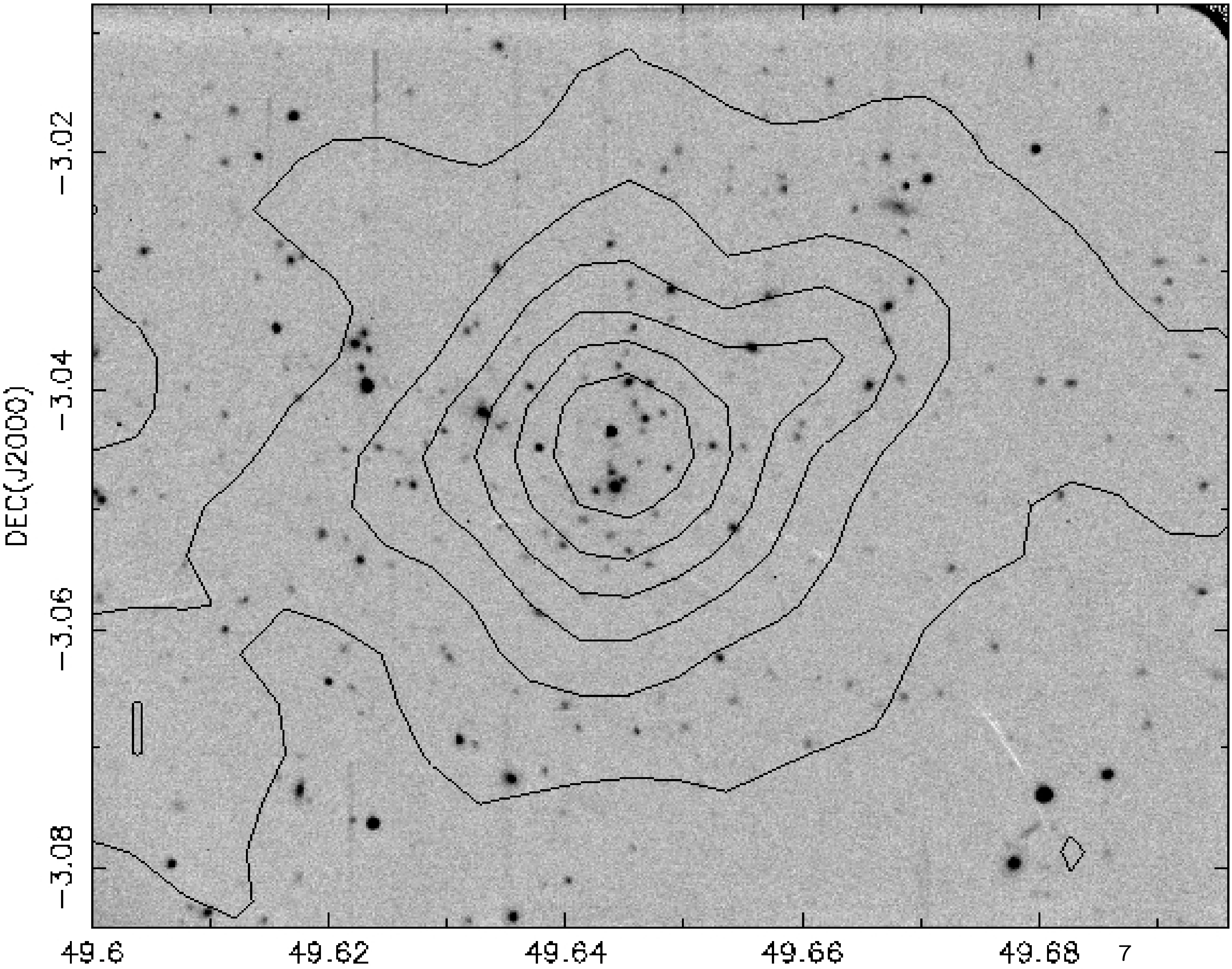
- Matched Filter: tuned to detect expected luminosity distribution (Schechter function) and number density profile (Plummer law)

- red sequence: model colors of brightest cluster galaxy (usually giant elliptical) with redshift, and look for E/S0 ridge line

- C4: Clustering of galaxies in 7-dimensional position and color space

- Friends-of-friends algorithm: only for spectroscopic sample

- Other wavelengths, especially X rays



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The mass of intracluster gas from X ray observations

- The emission mechanism: thermal bremsstrahlung (collisional deceleration of electrons)

- From the spectral shape: temperature of $\sim 10^8$ K!

- From total flux and distance: the X-ray luminosity $L_x \sim 5 \times 10^{44}$ erg/s, or $\sim 10^{11}$ $L_\odot$!

- This power is emitted from a sphere of radius $R \sim 3$ Mpc; we can estimate the volume density of free electrons, n_e, from $L_x = 4\pi R^3 L_{vol}/3$, where the volume luminosity density of thermal bremsstrahlung radiation is $L_{vol} = 1.4 \times 10^{-27} n_e^2 T^{1/2}$ erg/s/cm^3 (see textbook for details!)

- It follows that $n_e \sim 10^{-4}$ cm^{-3}. We can estimate the total mass of the gas, M, by assuming one proton for every electron, so $M = 4\pi R^3 n_e m_H/3$, and so $M = 3 \times 10^{14}\ M_\odot$.

- While this is about 20 times more mass than in all the stars, this is still only about 1/10 of the total mass (implied by dynamical measurements)!

Clusters in SDSS Data

- Surface density: $\sim$ 2 per deg^2 for $r_{Pet} < 21$ (about 20,000 clusters from SDSS)

- Mean distance between two clusters: $\sim$ 50 Mpc

- Richness: $\Lambda \approx 10\sqrt{N_{gal}}$, where N_{gal} is the number of E/S0 galaxies with $M_i < -20$ ($\sim$10-200)

- Velocity dispersion: $\sigma_v \approx 100\,\mathrm{km/s}\,\sqrt{N_{gal}}$

- Total luminosity: $L \approx 2 \times 10^{10} L_\odot\, N_{gal}$

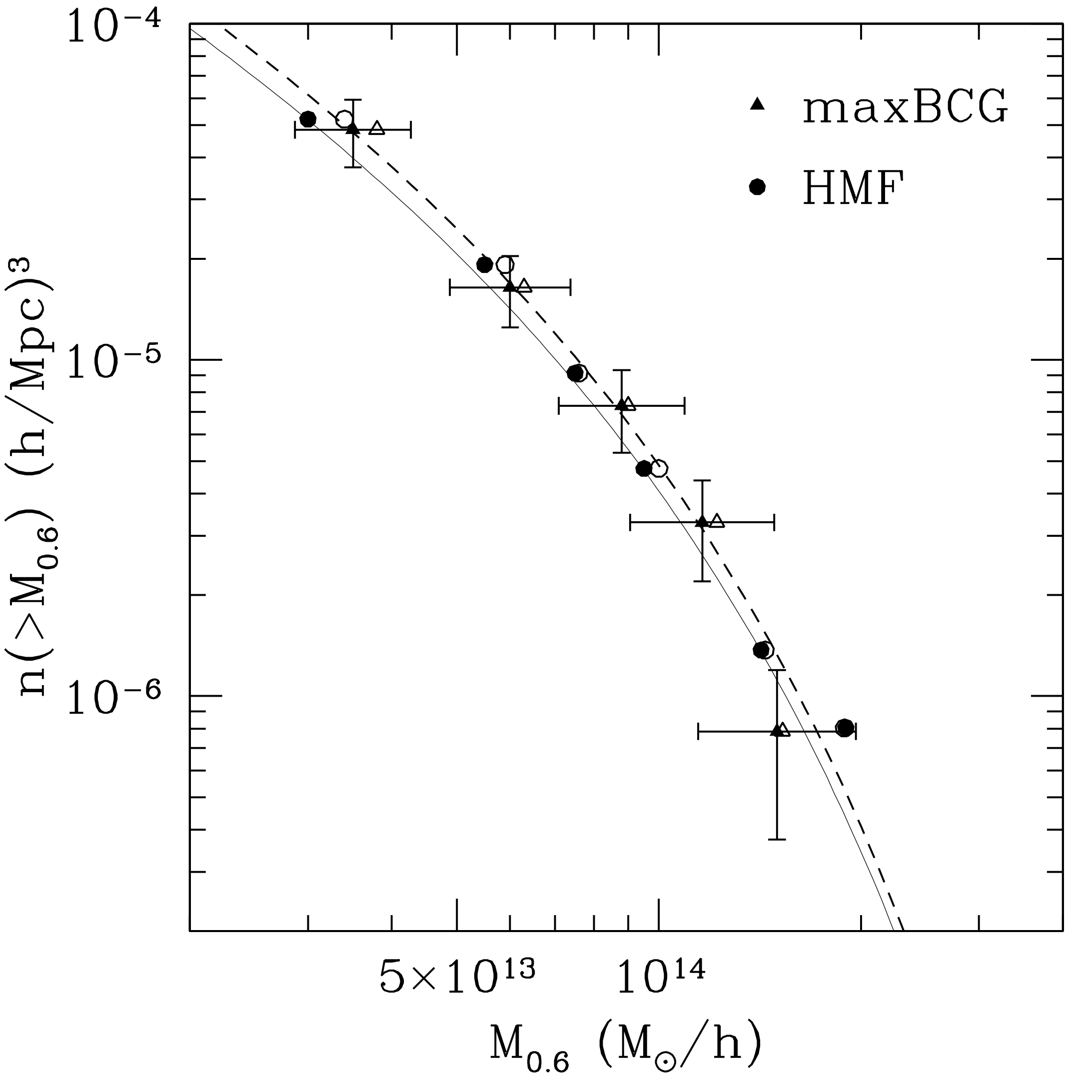
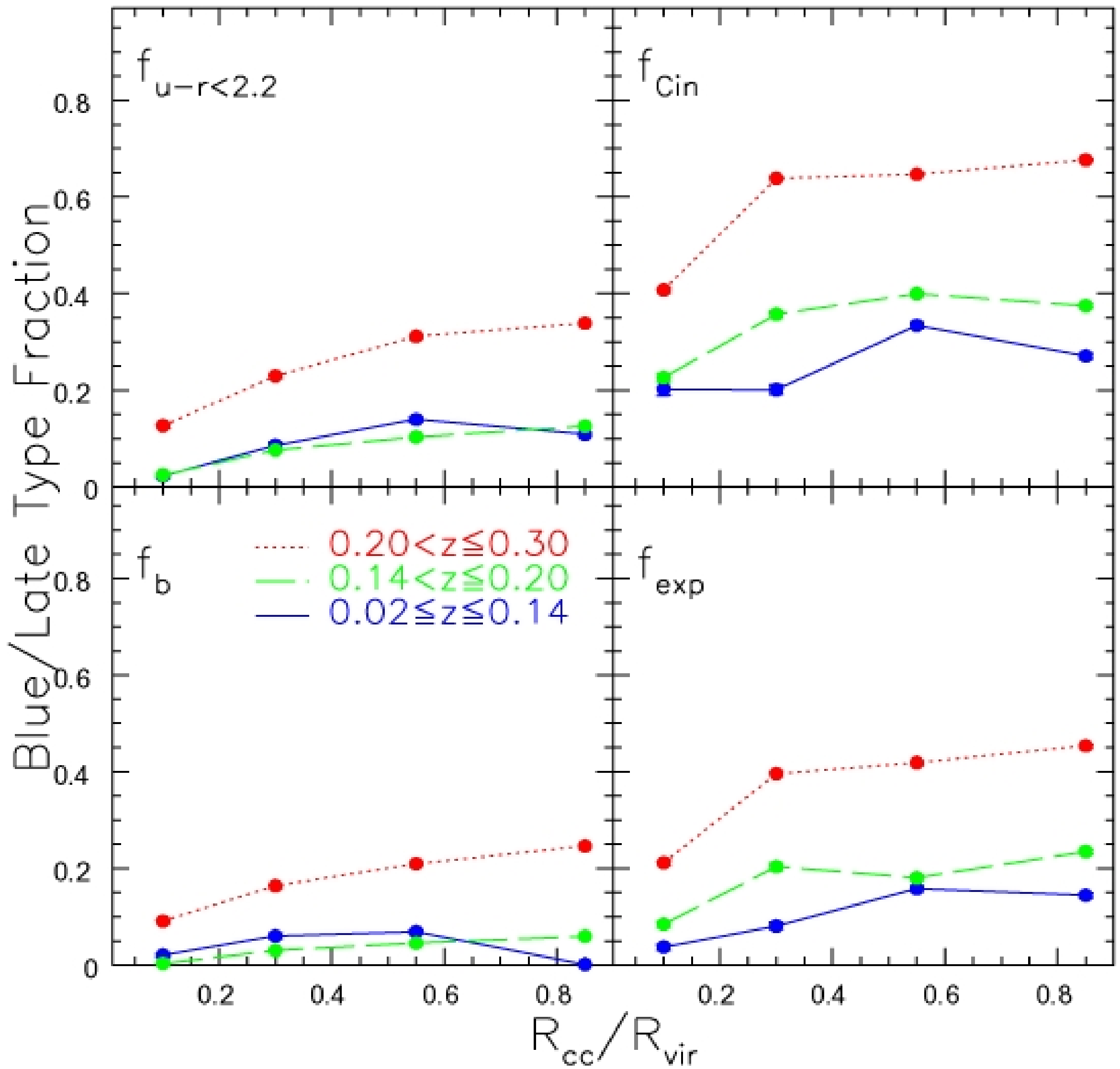


Fig. 5.— The maxBCG and the HMF cluster mass functions, showing masses determined from both luminosity – mass relation (solid triangles: maxBCG; solid circles: HMF) and velocity dispersion – mass relation (open triangles: maxBCG; open circles: HMF). The best-fit analytic models are shown by the dashed line (maxBCG; Ω_m= 0.195, σ_8= 0.90), and solid line (HMF; Ω_m= 0.175, σ_8= 0.92; as in Figure 2).

Cluster Mass Function

(Bahcall et al. 2003)

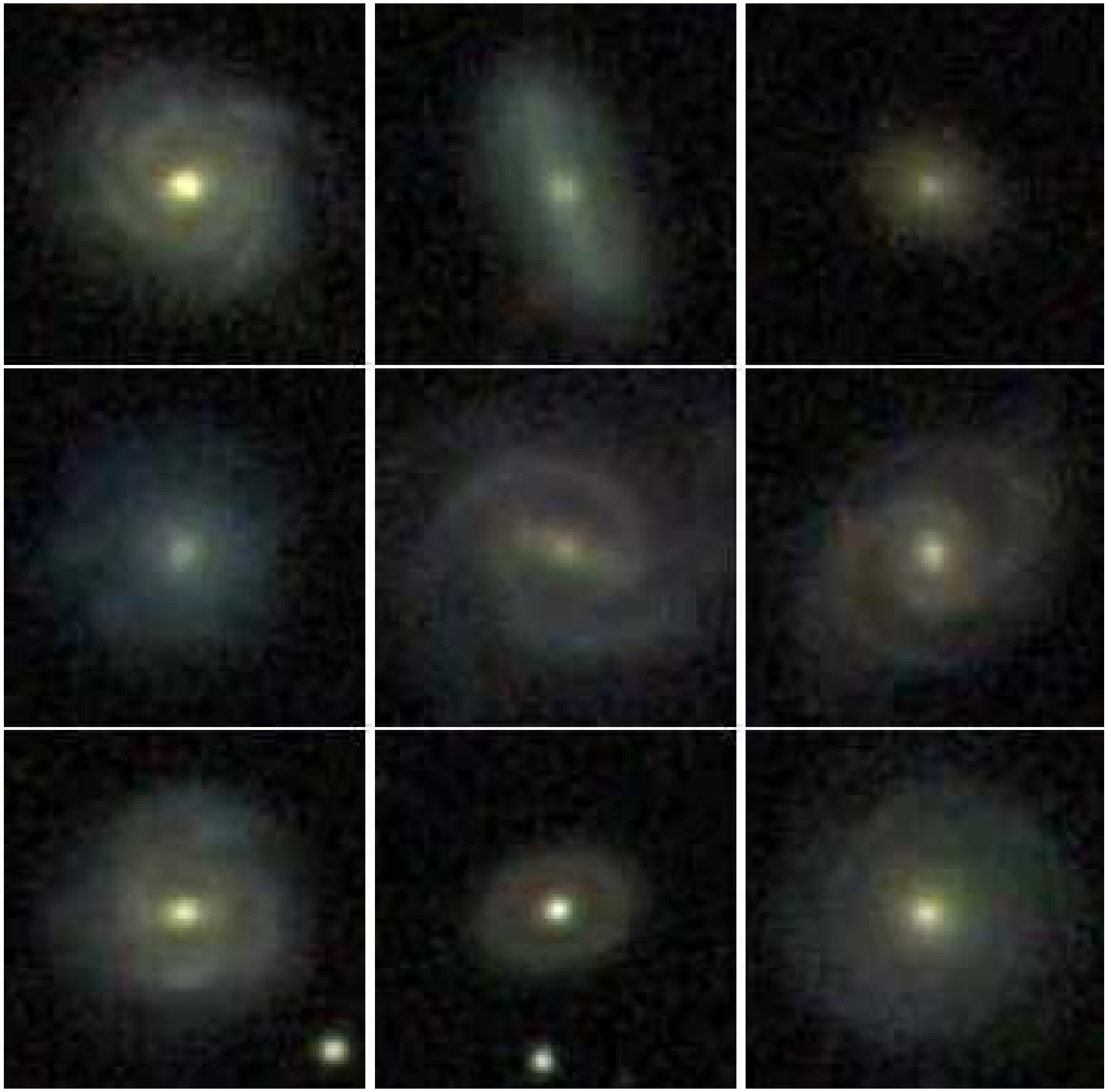
- maxBCG: triangles, MF: circles
- solid: mass from luminosity; open: mass from velocity dispersion
- lines: models ($\Omega_m \sim 0.2$, $\sigma_8 \sim 0.9$)
- Different methods agree well both cluster finding algorithms, and methods for estimating mass



Galaxy Type vs. Clustercentric Radius Relation

(Goto et al. 2004)

- All four methods for classifying galaxies show that red galaxies dominate the cluster centers

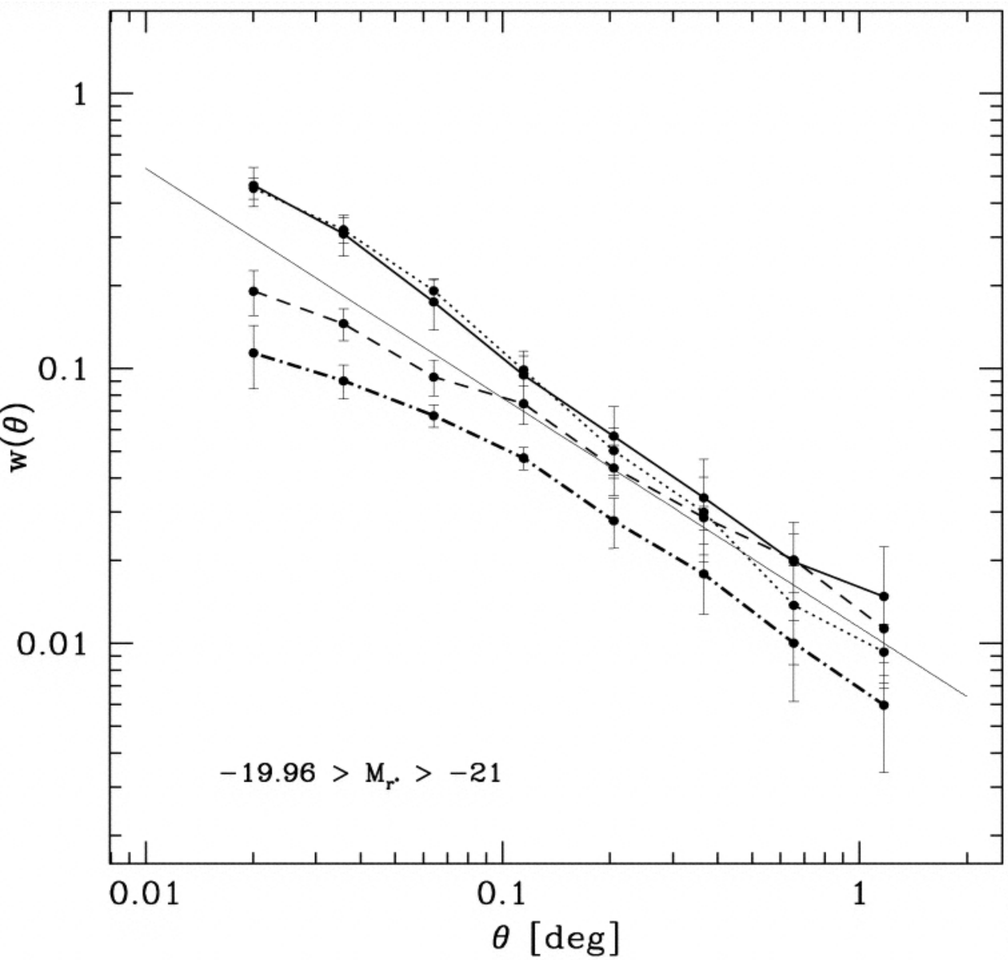


Galaxy Type vs. Clustercentric Radius Relation

(Goto et al. 2003)

- All four methods for classifying galaxies show that red galaxies dominate the cluster centers
- Around the radius where the density of blue galaxies starts decreasing ($\sim$ 1 virial radius), there is an excess of "anemic" spirals: morphologically spiral galaxies but without emission lines (no star formation). They represent 0.3% of all spiral galaxies.

Large-scale structure



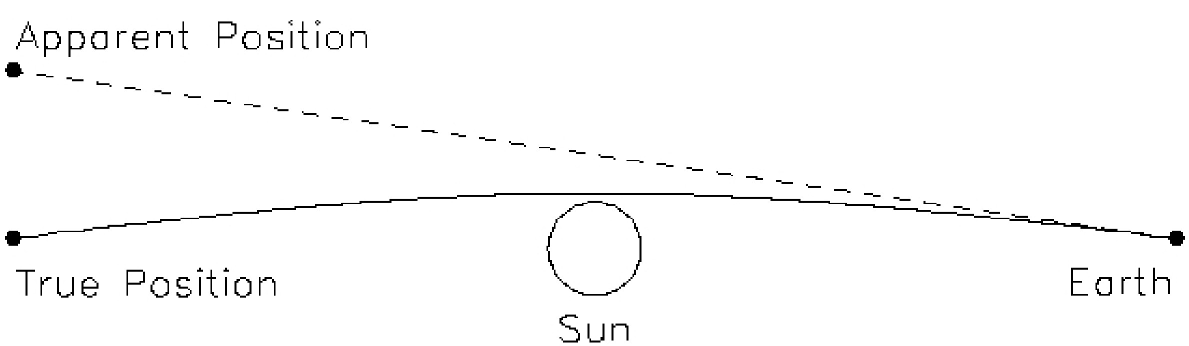
- Angular Correlation Function (ACF): the excess of pairs of galaxies as a function of separation, compared to a random distribution
- ACF $\propto r^{-0.7}$ on scales from arcmin to deg (based on 2 million SDSS galaxies)
- the clustering strength and the slope of the correlation function depend on the galaxy type: the correlation function is steeper for red than for blue galaxies
- correlations with luminosity (not clear how to disentagle the effect of luminosity-color correlation)
- Another approach: 3D Power Spectrum $P(k)$ (requires distance)

Deflection of light by gravitational field

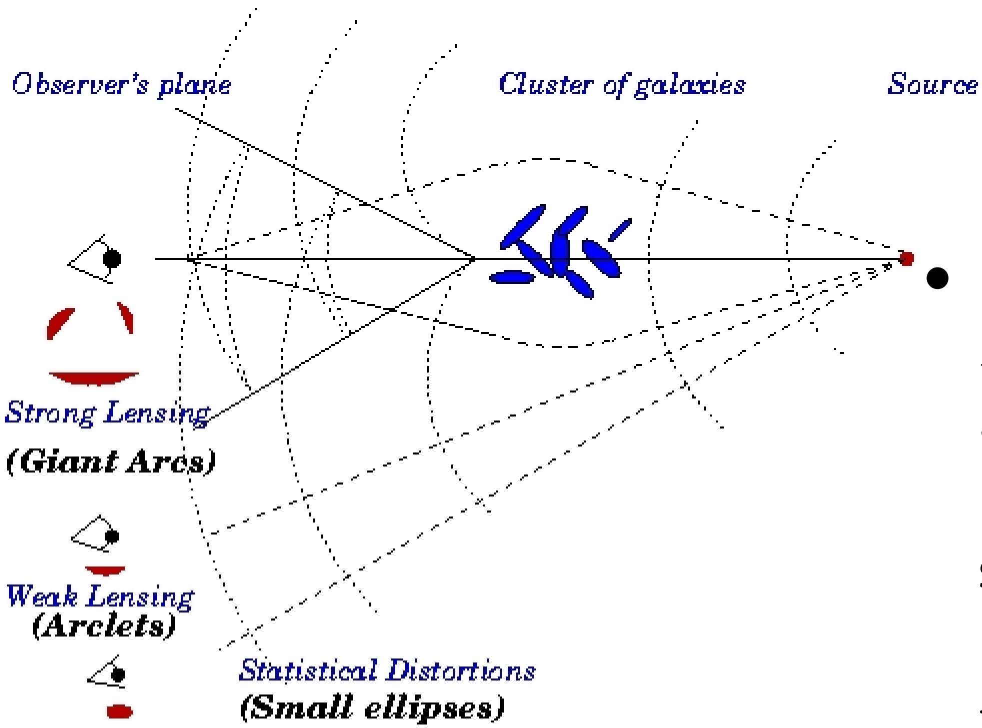
- Einstein (1916) predicted that the path of a beam of light could be deflected by the force of gravity.
- Einstein's prediction of the deflection angle, α, for a spherically symmetric mass is:

$$\alpha = \frac{4G}{c^2}\frac{M(< b)}{b} = 1.75'' \frac{M(< b)/M_\odot}{b/R_\odot} \tag{1}$$

  where $M(b)$ is the total mass within a distance b from the center of the mass.
- Confirmed observationally by Eddington et al. (1920)
- If M is $\sim 10^{12}\ M_\odot$ (galaxy) and $b \sim 10$ kpc, then $\alpha \sim$ arcmin – significant deflections and distortions!



FYI: there is a free iPhone app for “gravitationally lensing” an arbitrary image: **GravLensHD**

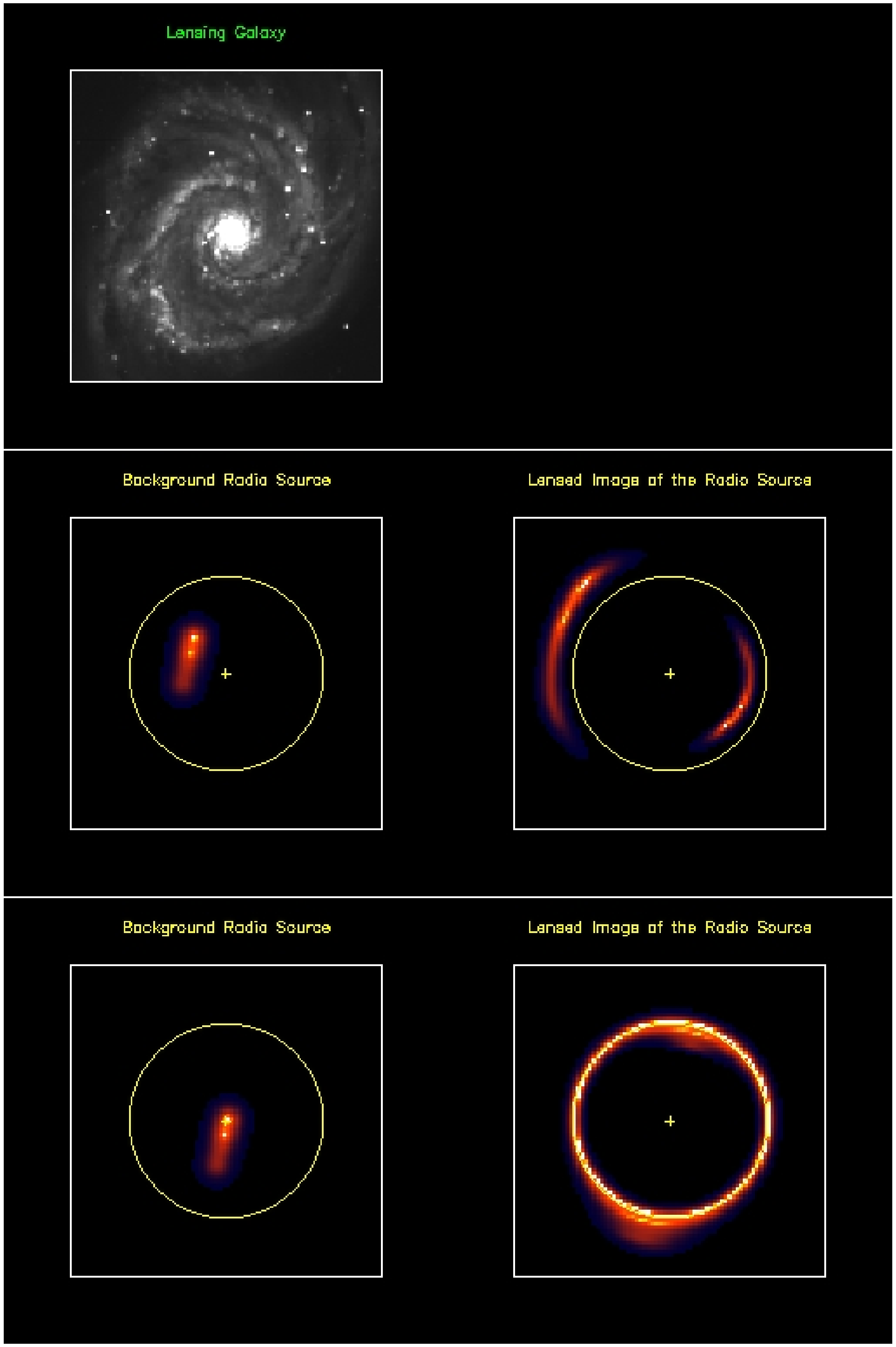


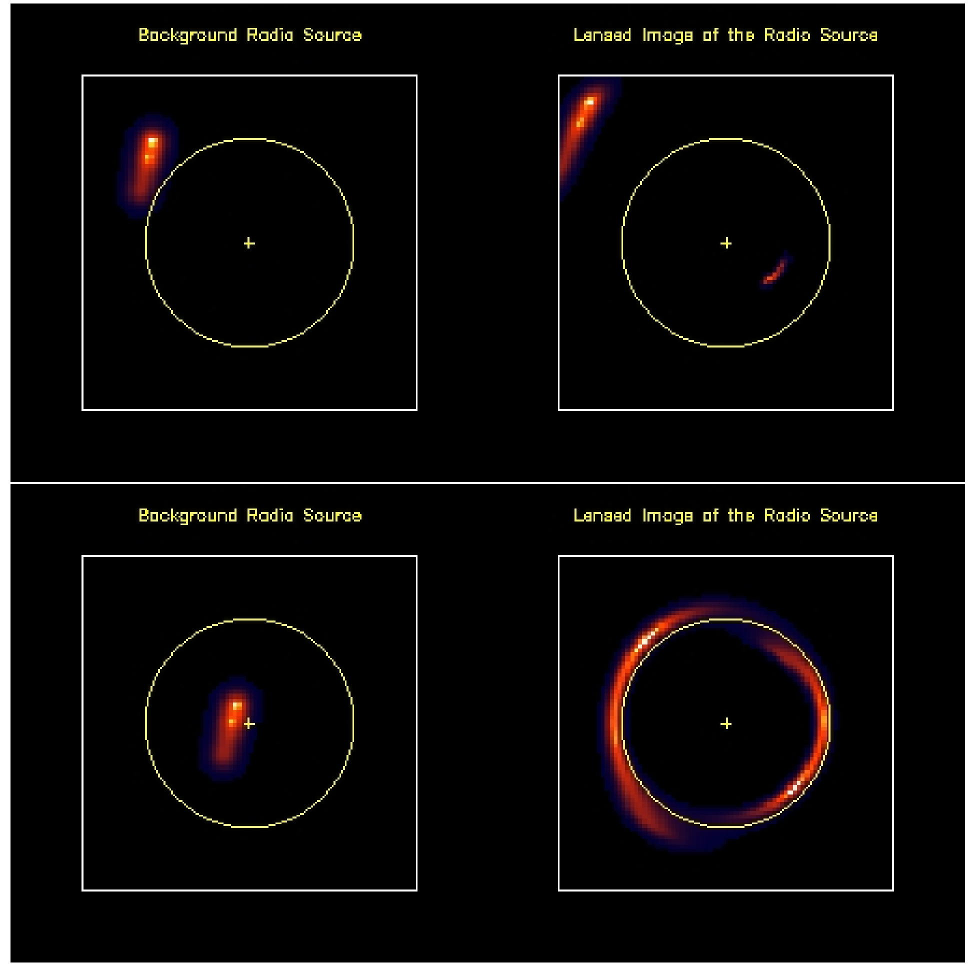
Lensing Regimes

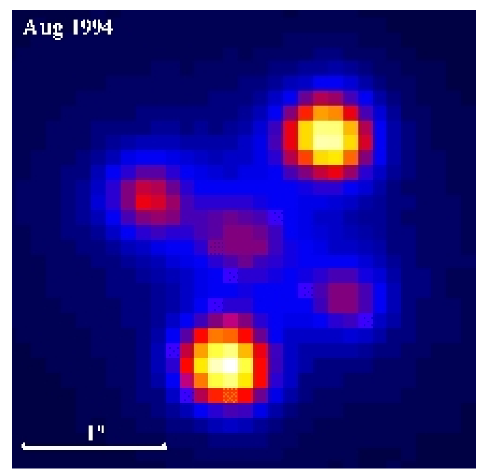
- A parameter that determines the morphology of lensed image is the Einstein angle:

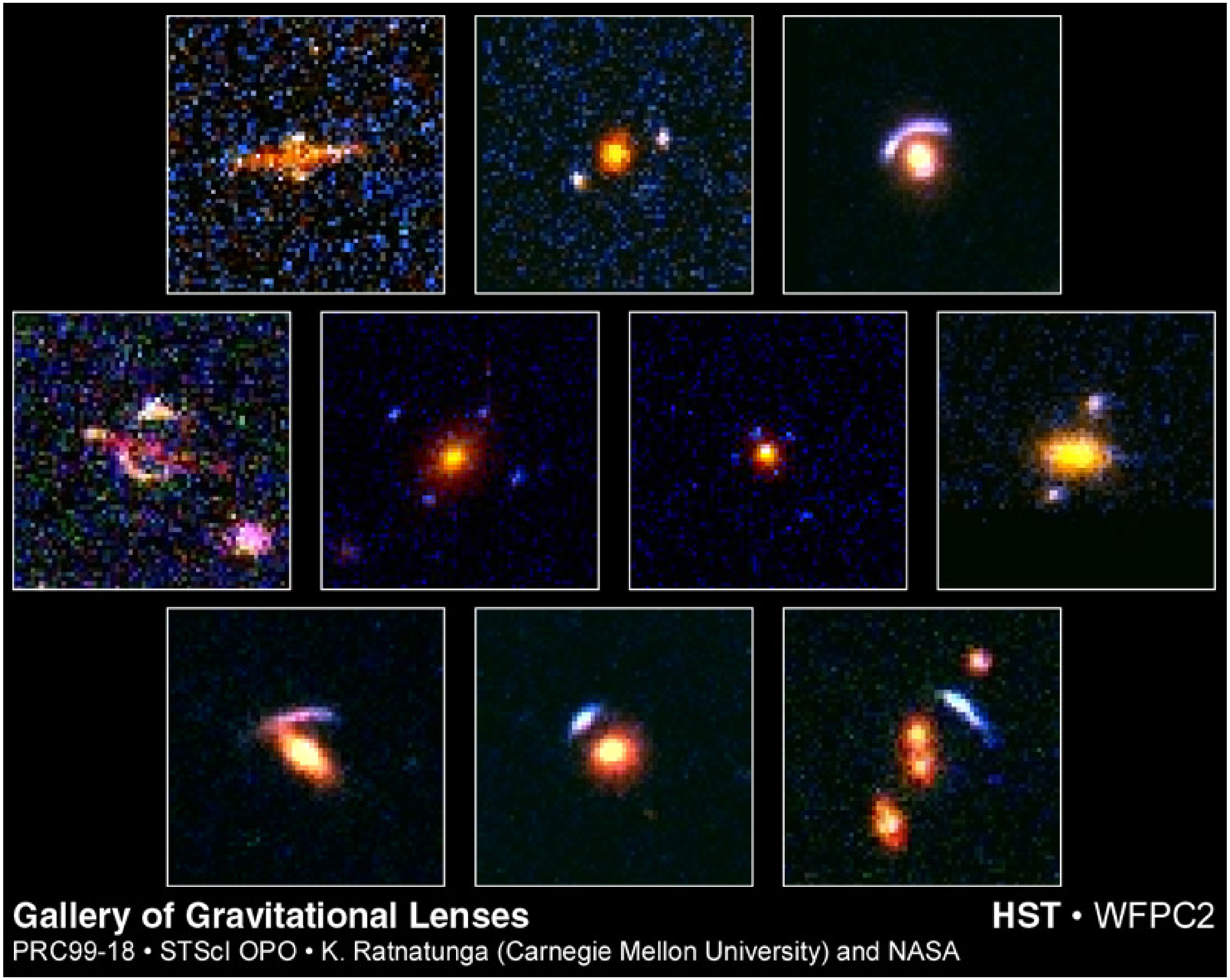
$$\theta_E^2 = \frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S} \qquad (2)$$

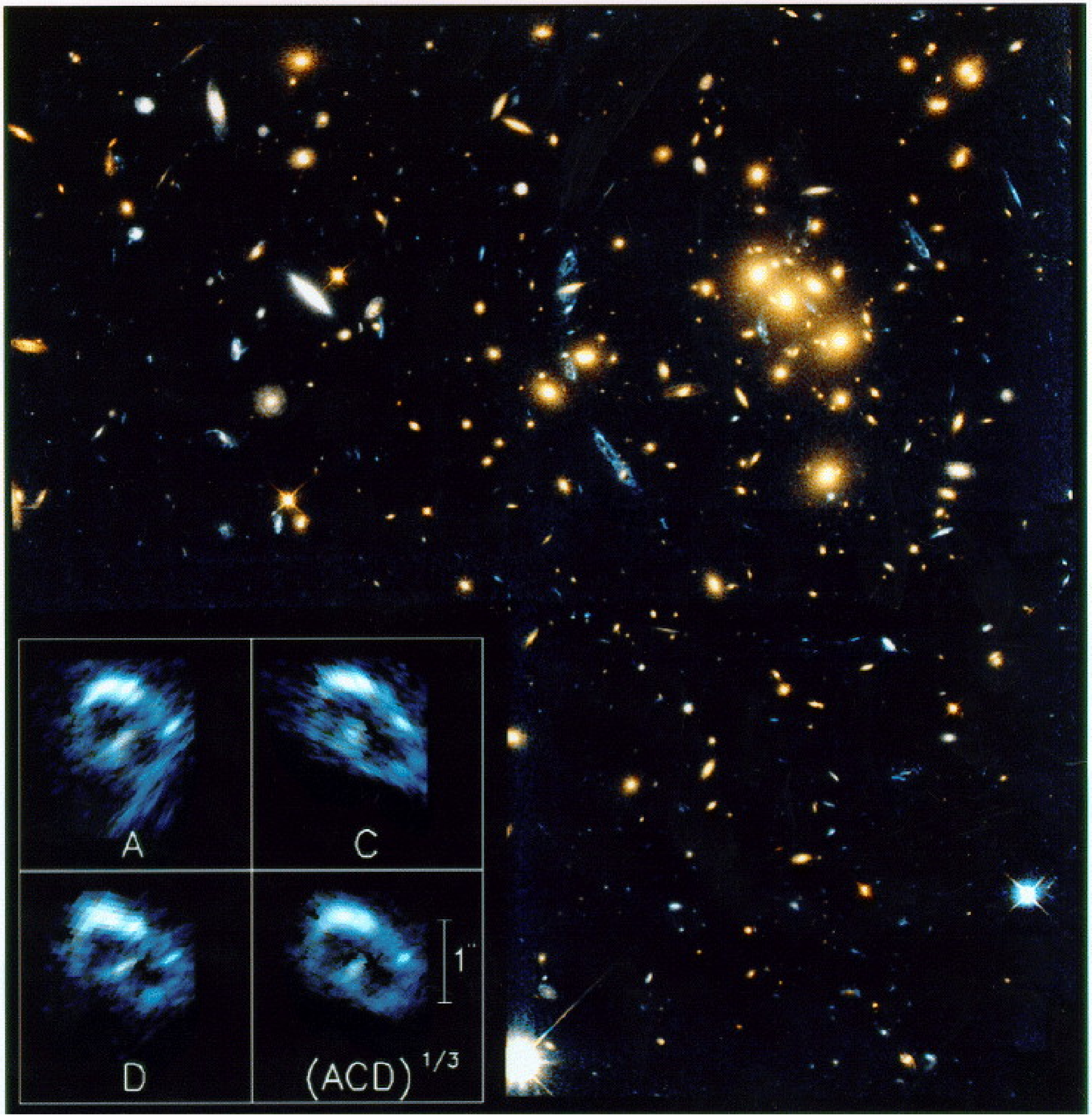
- Here, D_L is the distance to the lens, D_S is the distance to the source, and D_{LS} is the distance from the lens to the source (for Euclidean space $D_{LS} = D_S - D_L$, but for cosmological distances it is slightly different).
- Depending on D_S, D_L and lensing mass distribution, the lensed image can include multiple source images, rings, arcs
- Regimes: strong lensing, weak lensing, and statistical distortions


Lensing Galaxy
Background Radio Source
Lensed Image of the Radio Source
Background Radio Source
Lensed Image of the Radio Source


Background Radio Source
Lensed Image of the Radio Source
Background Radio Source
Lensed Image of the Radio Source


Aug 1994
1"


Gallery of Gravitational Lenses
HST • WFPC2
PRC99-18 • STScI OPO • K. Ratnatunga (Carnegie Mellon University) and NASA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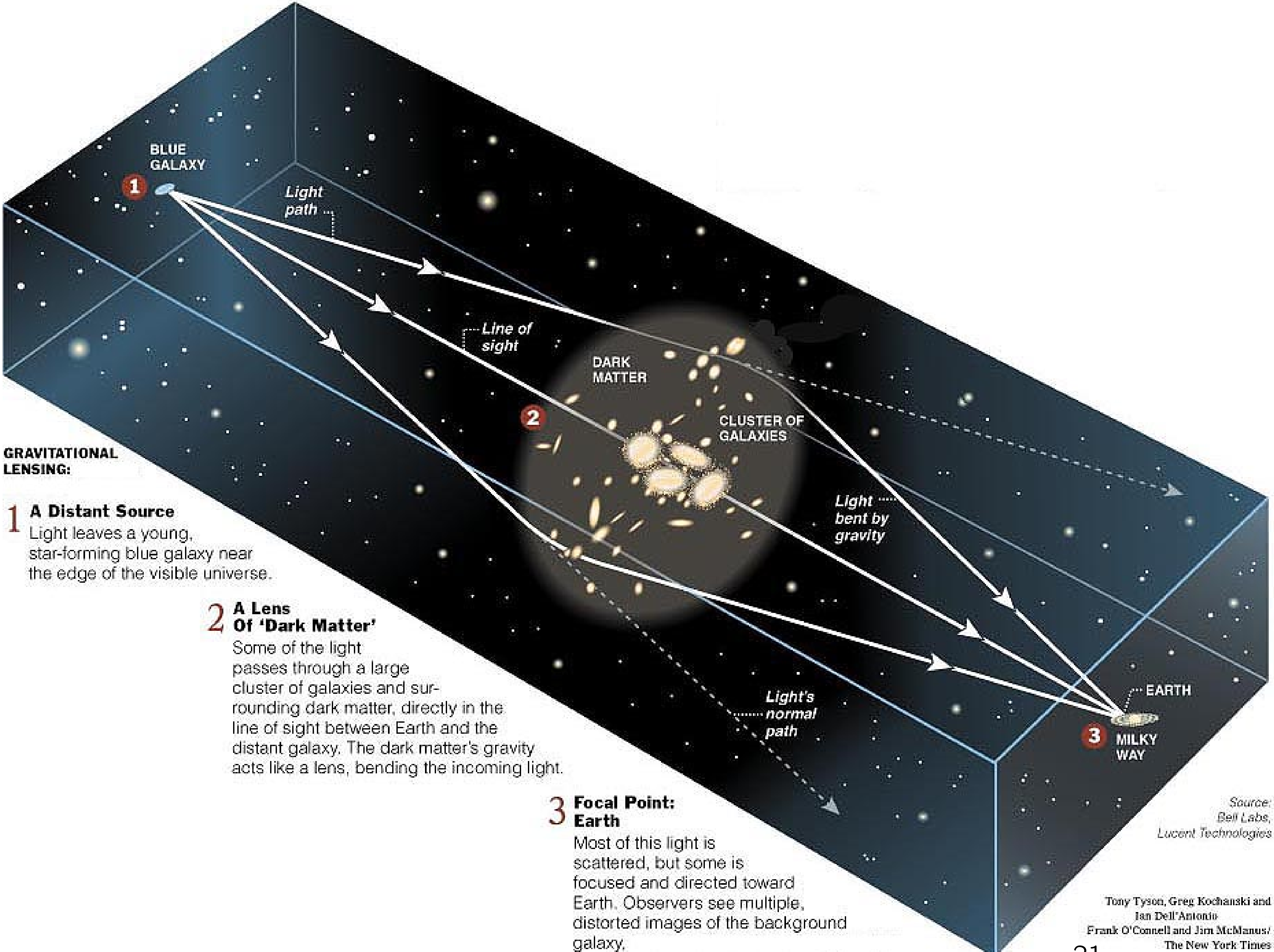
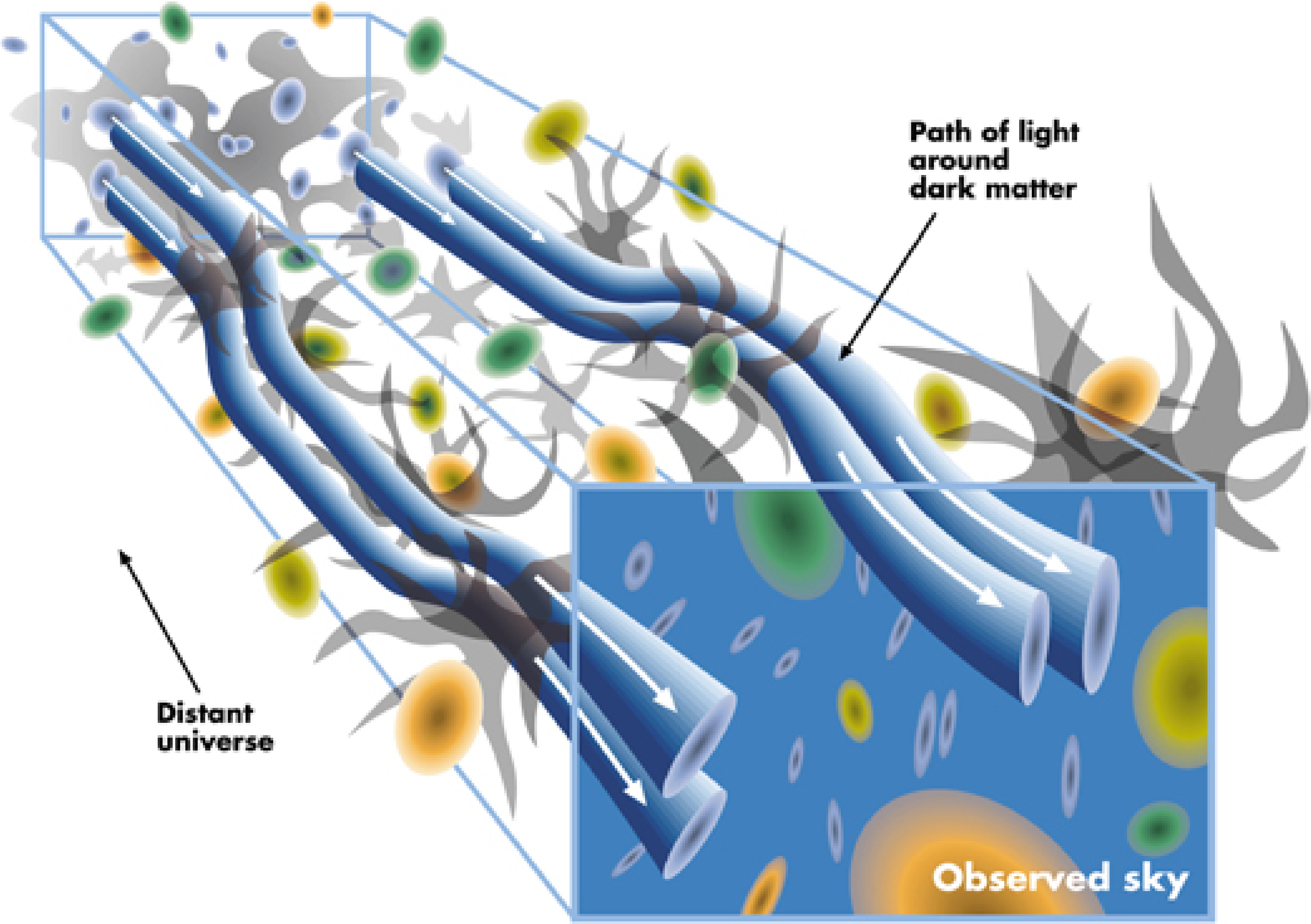
1''


BLUE GALAXY
Light path
Line of sight
DARK MATTER
CLUSTER OF GALAXIES
Light bent by gravity
Light's normal path
EARTH
MILKY WAY
GRAVITATIONAL LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.
3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Source: Bell Labs, Lucent Technologies
Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times


Path of light
around
dark matter
Distant
universe
Observed sky

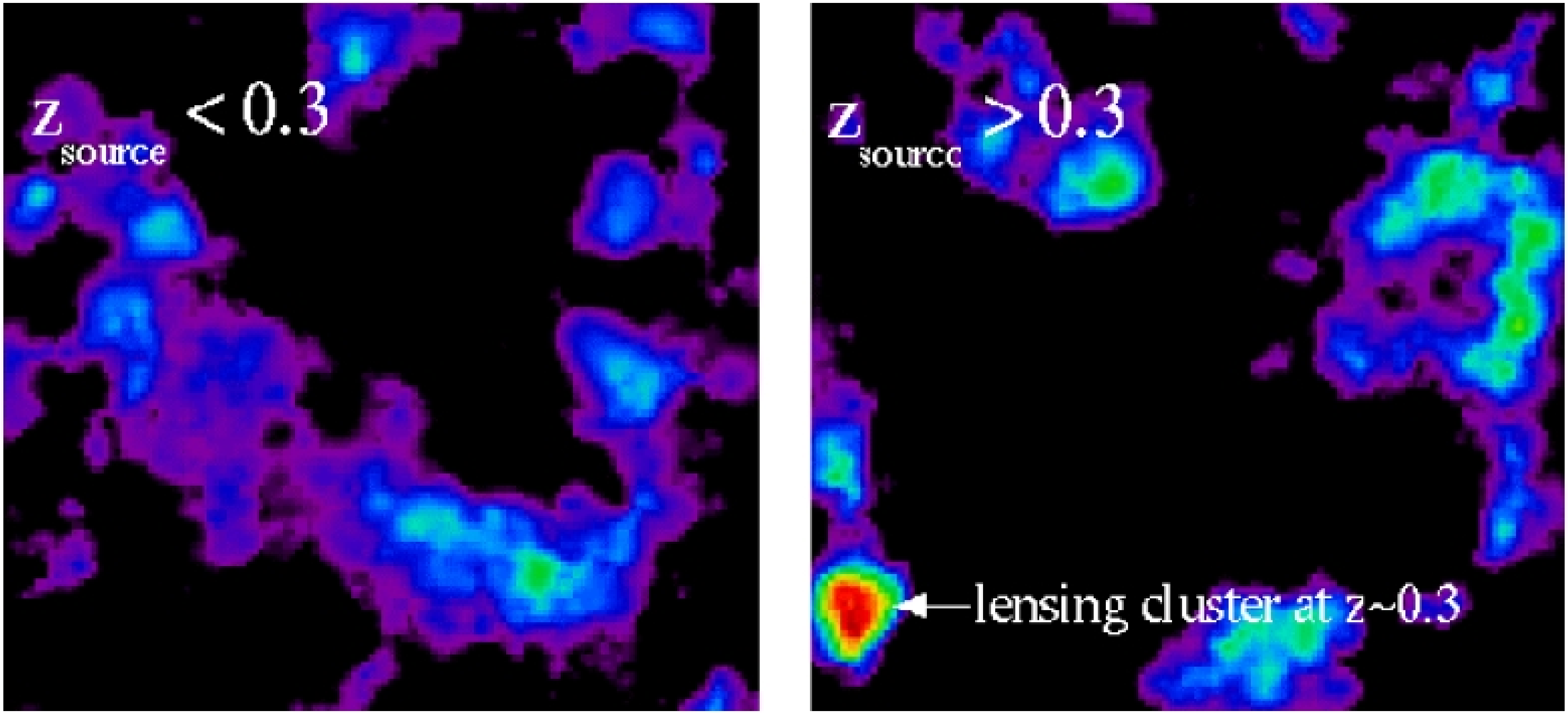
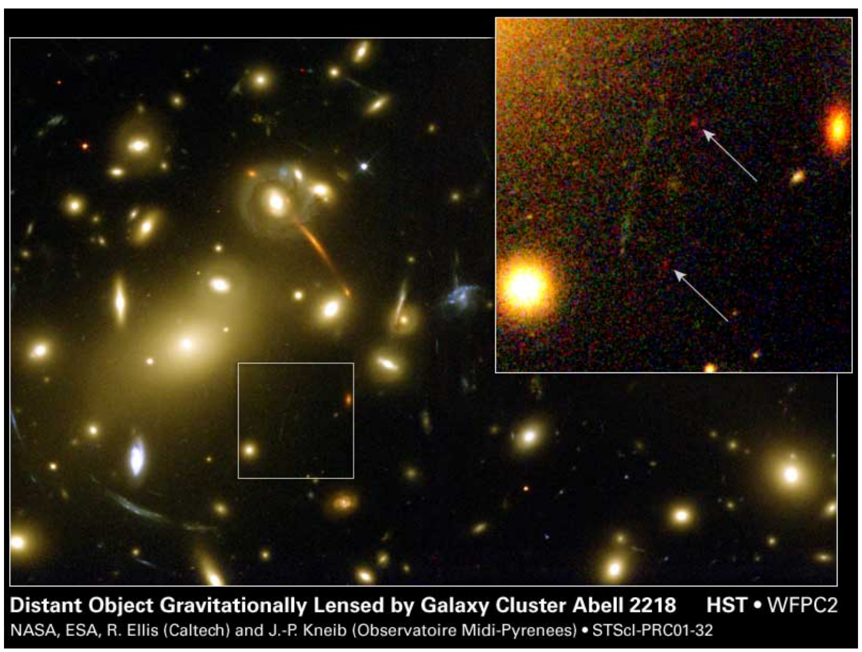
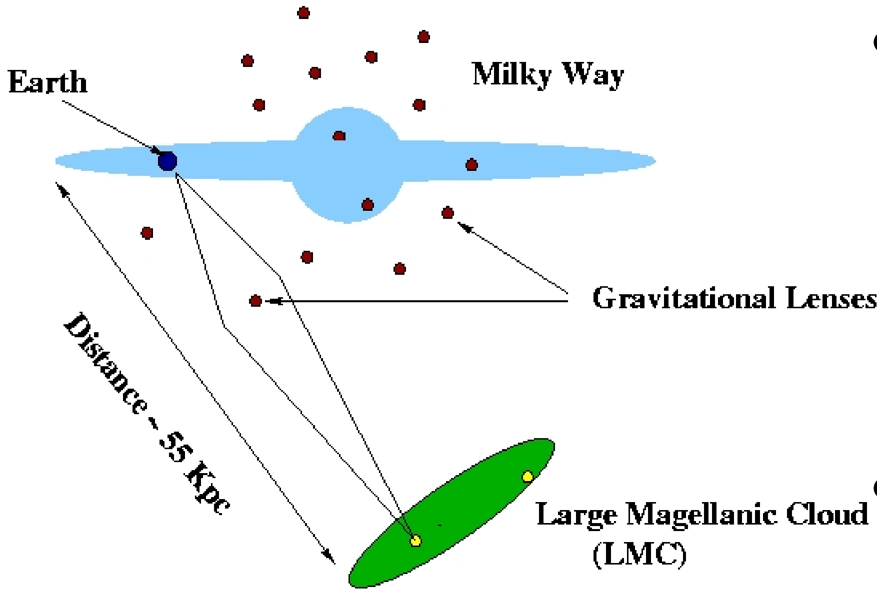


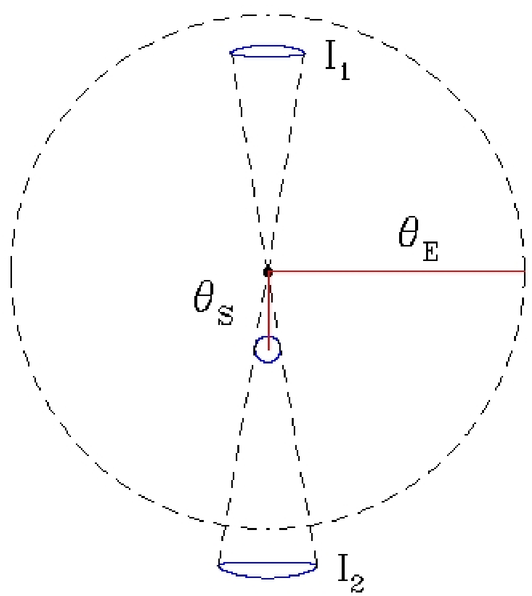
Figure 4. 3-D mass tomography from the Deep Lens Survey. These mass maps of a 40' field show two slices in redshift. Similar 3-D mass tomography has found clusters up to z=1.



Lensing Magnification

- Gravitational lenses are excellent probes of cosmological parameters
- Galaxy shear: tiny distortions of galaxy images. The future is in large faint samples – Large Synoptic Survey Telescope (LSST)!
- Gravitational lenses are giant telescopes: the magnification they provide allows detection of very distant galaxies
- Gravitationally lensed quasars allow studies of intergalactic medium and a direct determination of Hubble constant.





Microlensing

- The dark matter can be studied using a phenomenon called microlensing. This method was proposed in 1986 by Bohdan Paczynski, and is based on light magnification by a foreground compact dark object.
- With current telescopes the observer sees microlensing event as neither the splitting nor the distortion of the two images, but as one image (a blurring of the two microimages) that is brighter than the unlensed source.
- The magnification A by which the blurred combined image is brighter depends on the angular separation between the background source and the lens θ_S, compared to the angular size of the Einstein ring

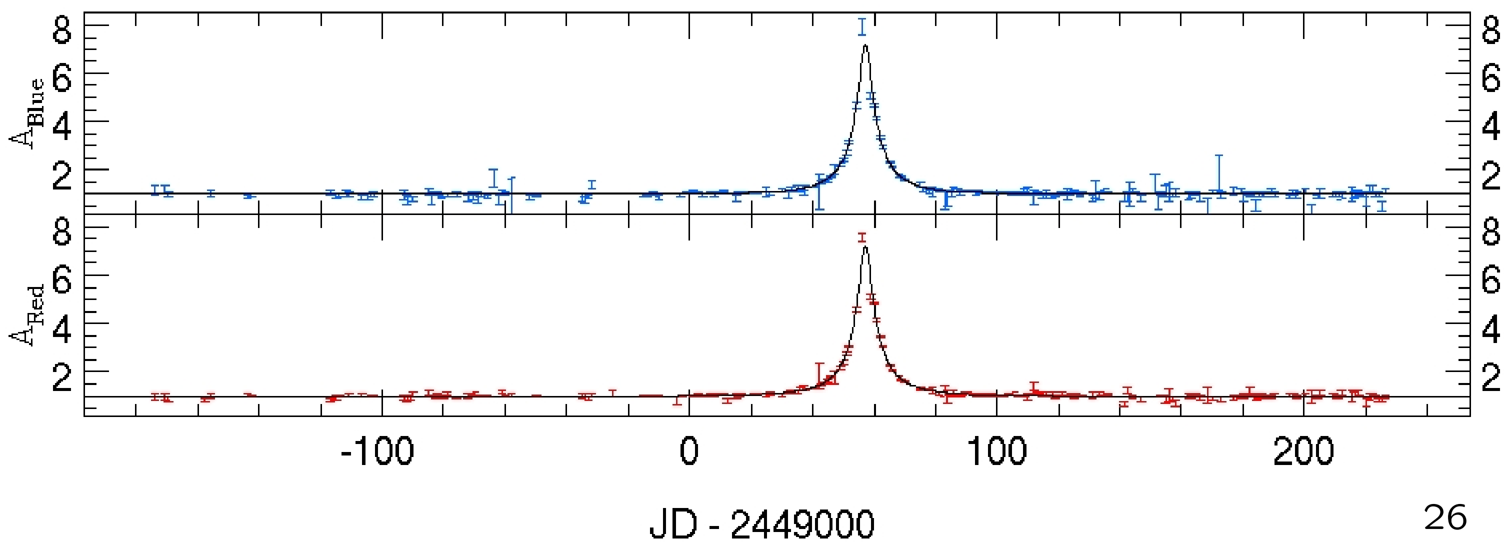
Microlensing

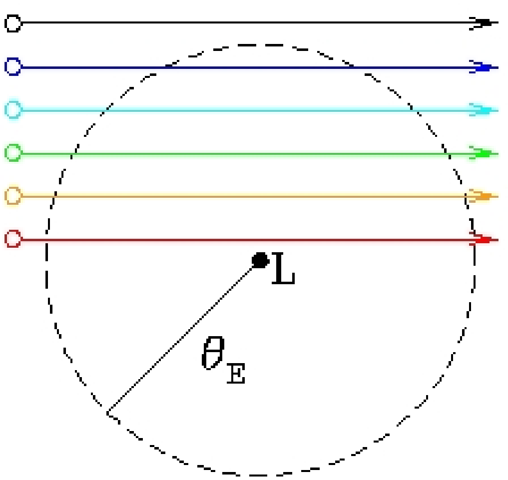
- Magnification A is

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \tag{3}$$

  where $u = \theta_S/\theta_E$ (what is A for $\theta_S = 0$?)

- Paczynski's idea was implemented by three major surveys: OGLE, MACHO and EROS. Although the probability that a star is lensed is only $\sim 10^{-6}$, all three surveys reported detection of microlensing events in 1993.
- It seems today that this method is more useful for understanding stars in the Milky Way, than for characterizing dark matter.





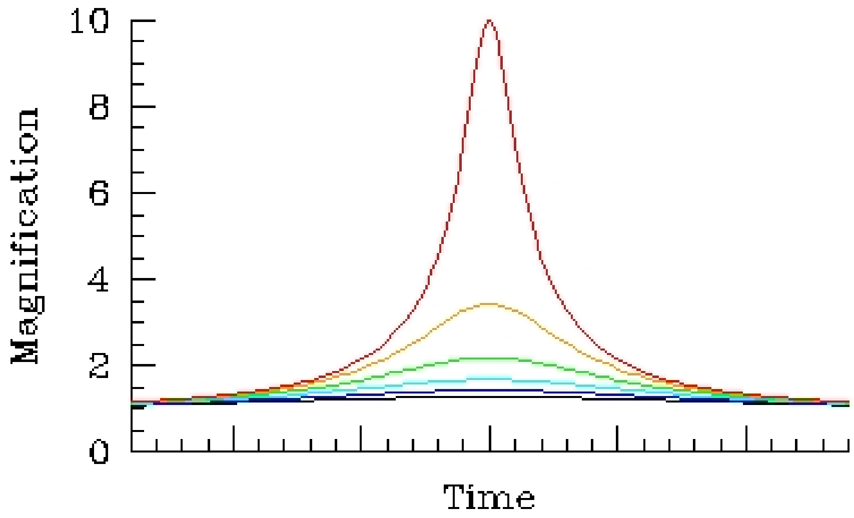


Fig. 4 --- Background source stars may pass behind the lens with different minimum angular separations. Those that pass closest to the lens (in projection on the sky) will experience the greatest magnification in their brightness. Sources that pass an angular distance from the lens equal to the Einstein ring radius θ_E will be magnified by a factor 1.34. The light curves (brightness of the sources as a function of time) are shown on the right for each of the possible paths shown on the left. Since each of the random possibilities for source position shown above is equally likely, each of the resulting light curves show below have equal probability. Click on figures for a zoom.

The length of time over which this takes place and thus the duration of the microlensing event depends on the mass of the lens, the speed of the source across the sky, and distances of the observer to the lens and source. Faster motion and smaller lens masses will produce shorter microlensing ``events." For stellar mass lenses traveling at speeds typical for stars in the Milky Way, microlensing events should last a few weeks to a few months. Since the focusing of the light rays is independent of wavelength, microlensing light curves are ``achromatic," that is, they have the same shape regardless of the filter in the telescope camera.

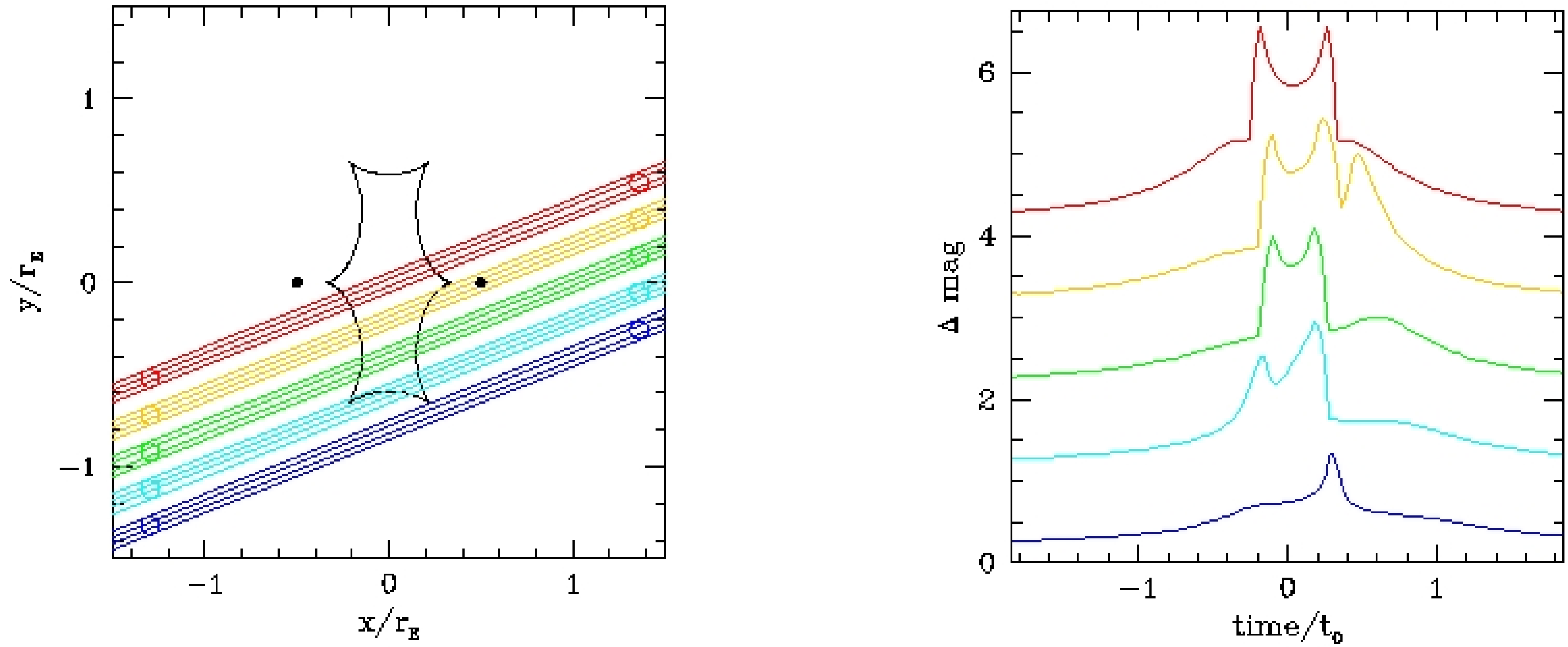
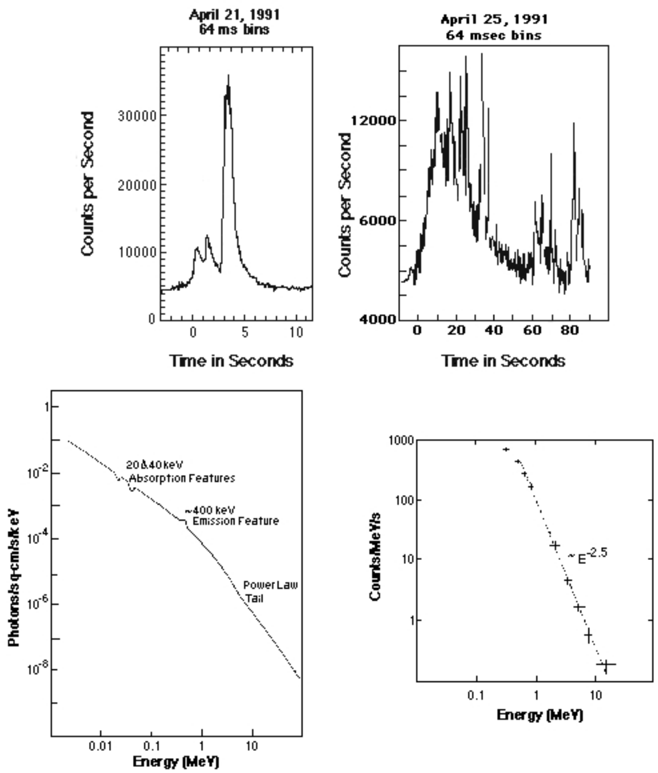
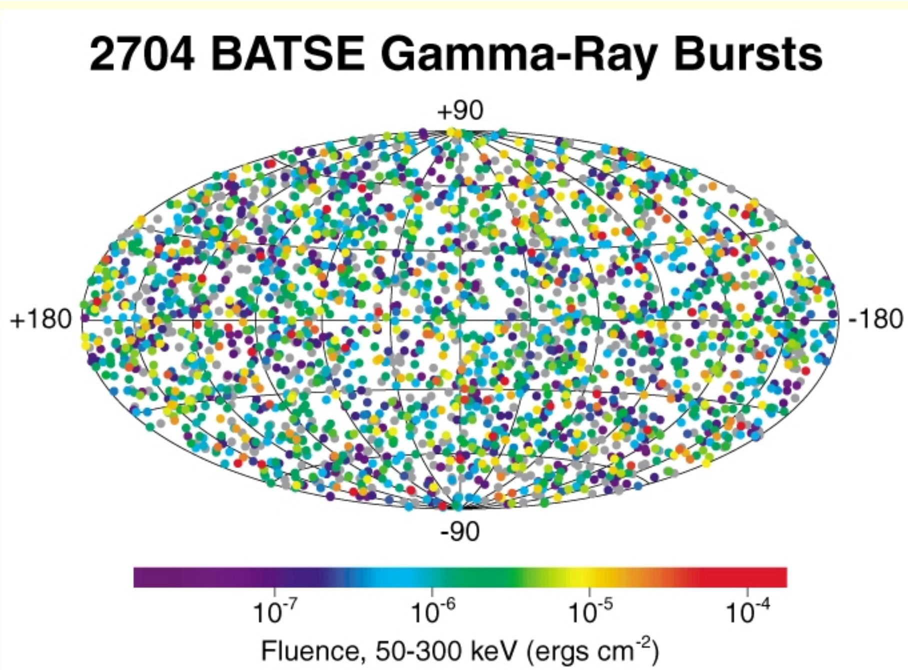


Fig. 9 --- Left: An equal mass double lens (two black dots) creates a caustic structure --- regions where the combined effect of both lenses is enormous --- shown here as the solid black line between the two lenses. Right: The light curves of sources passing behind this caustic structure will exhibit rapid increases of brightness at the moment of crossing. The exact light curve shape depends on the path (shown as the colored lines in the left-hand figure) that the source takes as well as on the mass ratio of the lens and their angular separation. Click on the figures for a zoom. (Adapted from Paczynski 1996.)

By carefully measuring the anomalous structure in a binary lens light curve, the ratio of the mass of one lens to the mass of its partner can be measured. One can also measure the angular distance between the lenses at the time the anomaly occurred as a fraction of their Einstein ring radii. Microlensing thus gives astronomers a way to determine which types of binary stars are common in our Galaxy.





Gamma-ray bursts

- Short-lived bursts of gamma-ray photons, the most energetic form of light. Discovered serendipitously in the late 1960s by U.S. military satellites.
- Until recently, it wasn't clear whether they originated in the Solar System, the Milky Way, or at cosmological distances! The arguments were nicely summarized in the Paczynski–Lamb debate (1995), modeled after the Shapley-Curtis 1920 debate.
- Today there is a growing consensus that most gamma-ray bursts are associated with supernovae in distant galaxies.
- For a recent review, see Meszaros (2002, astro-ph/0111170)